Spatial pattern of soil carbon and nutrient storage at the Alpine tundra ecosystem of Changbai Mountain, China

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Abstract: In August 2003, we investigated spatial pattern in soil carbon and nutrients in the Alpine tundra of Changbai Mountain, Jilin Province, China. The analytical results showed that the soil C concentrations at different depths were significantly (p<0.05) higher in Meadow alpine tundra vegetation than that in other vegetation types; the soil C (including inorganic carbon) concentrations at layer below 10 cm are significantly (p<0.05) higher than at layer of 10–20 cm among the different vegetation types; the spatial distribution of soil N concentration at top surface of 0-10 cm depth was similar to that at 10–20 cm; the soil P concentrations at different depths were significantly (p<0.05) lower at Lithic alpine tundra vegetation than that at other vegetation types; soil K concentration was significantly (p<0.05) higher in Felsenmeer alpine tundra vegetation and Lithic alpine tundra vegetation than that in Typical alpine tundra, Meadow alpine tundra, and Swamp alpine tundra vegetations.. However, the soil K had not significant change at different soil depths of each vegetation type. Soil S concentration was dramatically higher in Meadow alpine tundra vegetation than that in other vegetation types. For each vegetation type, the ratios of C: N, C: P, C: K and C: S generally decreased with soil depth. The ratio of C: N was significantly higher at 0–10 cm than that at 10–20 cm for all vegetation types except at the top layer of the Swamp alpine tundra vegetation. Our study showed that soil C and nutrients storage were significantly spatial heterogeneity.

Keywords Soil carbon storage; Soil nutrients; Alpine tundra ecosystem; Vegetation type; Changbai Mountain
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Introduction

Terrestrial ecosystems contain large amounts of organic carbon, which is about three times the amount of carbon as found in the atmosphere (Watson *et al.* 1990), and they play a significant role in the uptake of CO_2 in the overall budget (Schimel *et al.* 1995; Fan *et al.* 1998; Houghton 1999; Rayner *et al.* 1999). The effects of land use change on soil carbon stocks are of concern in the context of international policy agreements on greenhouse gas emissions mitigation (IGBP Terrestrial Carbon Working Group, 1998). However, how to manage current terrestrial ecosystems to conserve existing carbon stocks (especially the soil pool) is a new challenge (Maihi *et al.* 1999). Most of publications were focused on tropical areas (Camargo *et al.* 1999), and few studies were done on change of soil carbon storage associated with soil nutrients in temperate Alpine tundra ecosystems, which of terrestrial ecosystem is the most sensitive to climate change. More studies in different tundra ecosystems on earth are needed to verify the above conclusion in order to meet the challenge of managing soil carbon and nutrients stocks world-wide.

Now the Alpine tundra ecosystem of Changbai Mountain is covered with abundant herbs and shrubs after volcano eruption in 1702. Because of development of tourist trade, increasing human population in this area, and global climate change, much of Alpine tundra was degraded. The aim of this research is to study soil carbon and nutrient storage change and to test the hypothesis that the difference of soil C and nutrients stocks is significant during vegetation restoration after volcano eruption.

Methods

Research area

This research was carried out in the Alpine tundra ecosystem, which is one of the typical landscape types of China, at Changbai Mountain Natural Reserve in Northeast China. The location is at latitude 42°24'N and longitude 128°05'E. The climate is characterized by cold weather during long winter, and short, cool summers. The annual mean temperature in the study area is –7.4 °C, and the annual average precipitation ranges from 700 to 1400 mm. In this study, the representative examples of all vegetation types were located at the elevation of 1 950–2 650 m on the northern slope of the Changbai Mountain. The study sites are within an area of 15195 hm^2. The topographical, geomorphic and hydrological conditions are relatively complicated. The soil in this area is Alpine tundra earths. Its properties are: pH range 4.61–6.02, soil bulk density (0–20 cm) about 0.64–0.97 $g \cdot cm^{-3}$, organic matter 0.76–33 $g \cdot kg^{-1}$, total N 0.05–0.69 $g \cdot kg^{-1}$ and total P 0.01–0.16 $g \cdot kg^{-1}$. The area was volcanic ash before covered by Alpine tundra vegetation. The Alpine tundra is dominated by

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herbaceous plants, shrubs, moss and lichen. The main species of shrubs were *Dryas octopetala* var. *asiatica, Vaccinium jliginosum* var. *alpinum, Vaccinium vitis-idaea, Rhododendron confertissimum, Rhododendron chrysanthum, Phyllodoce caerulea, Vaccinium uliginosum.*

Experimental design and measurement methods

In August 2003, four soil profiles were randomly chosen on the representative sites of each vegetation type with the same plant species composition and similar geomorphic and hydrological condition,. The soil bulk density was measured at the depths of 5 cm and 15 cm, and the data of soil bulk densities were adjusted for stone content at each vegetation type. Four soil samples (>200 g) at each depth of 0–10, 10–20 cm were collected from each profile to analyze the content of C, N, P, K and S. There were total 256 samples. All these soil samples were put into sealed hop-pockets and kept at 4°C until they were used to analyze the nutrients by standard procedures. The total content of C in soil samples was analyzed by CNS-Analysator LECO SC444; organic carbon was measured by spectrophotometer after digestion with $K_2Cr_2O_7/H_2SO_4$; inorganic carbon was calculated as total carbon minus organic carbon; total N was measured by Kjeldahl; K, P and S were measured by inductive coupled plasma spectrometry (ICPS) after digestion with $HNO_3/HClO_4$. The precision of all measurements was 0.01 units. The average of soil bulk densities, nutrient concentrations and their standard deviations were used in this study. The total stock (C_t, g·cm^{-2}) of soil C, N, P, K, and S were calculated as following (Guo and Gifford, 2002):

$$C_t = BD * C_c * D$$

where *BD* is the soil bulk density (g·cm^{-3}); C_c (%) is the soil nutrient concentration; *D* is the soil sampling depth (cm).

The t-test was used to compare the differences in soil C and nutrients at different vegetation types. The results were considered significant when $p < 0.05$. The analyses were performed using SPSS.

Results and analysis

Spatial distribution of soil carbon

The concentrations of soil total C at different depths were significantly ($p<0.05$) higher at Meadow alpine tundra vegetation (MA) than that at other vegetation types. The soil total carbon (including inorganic carbon) concentrations below 10 cm depth are significantly ($p<0.05$) higher that in 10–20 cm at each vegetation type of Alpine tundra ecosystem (Table 1, Fig. 1 A, B). The soil organic C and total C were similar between Felsenmeer alpine tundra vegetation (FA) and Lithic alpine tundra vegetation (LA) at the top surface depth while similar among FA, LA and Typical alpine tundra vegetation (TA) at the depth of 10–20 cm. Soil organic C concentration decreased dramatically from MA to LA or FA. Human activities (mainly tourist trade) could slightly affect the soil organic C storage after vegetation pattern was formed in this area. But climate change could dramatically affect the soil organic C storage currently. The carbon storage had similar change at different depths of different vegetation types (Table 2). In this study, we assumed that the FA possessed 100% of soil C, N, P, K, and S. After the FA was succeeded into the LA, TA, MA and Swamp alpine tundra vegetation (SA), the soil organic carbon increased significantly while the soil inorganic carbon decreased dramatically. Although it was not statistically significant, the soil TC was slightly higher in MA.

Table 1. Soil nutrient concentrations at different depths of different vegetation types (g C per 100 g)

Nutrient	Soil depth /cm	Felsenmeer alpine tundra vegetation	Lithic alpine tundra vegetation	Typical alpine tundra vegetation	Meadow alpine tundra vegetation	Swamp alpine tundra vegetation
Soil organic carbon	0–10	5.16(0.51)	5.58(0.25)	6.04(0.86)	8.22*(1.78)	6.38*(1.69)
	10–20	3.75(0.86)	3.73(0.46)	3.75(0.42)	5.68*(1.09)	3.09(0.35)
Total carbon	0–10	7.37(0.74)	7.97(0.36)	8.62*(1.23)	11.75*(2.54)	9.11*(2.41)
	10–20	5.32(1.23)	5.33(0.65)	5.36(0.6)	8.12*(1.56)	4.42(0.5)
Total nitrogen	0–10	0.34(0.07)	0.32(0.03)	0.32(0.02)	0.54*(0.15)	0.33(0.14)
	10–20	0.22(0.02)	0.24(0.03)	0.23(0.02)	0.34*(0.03)	0.18(0.03)
Total phosphorus	0–10	0.06(0.05)	0.03(0.02)	0.08(0.06)	0.1*(0.06)	0.18(0.03)
	10–20	0.05(0.03)	0.03(0.01)	0.09*(0.04)	0.12*(0.03)	0.14*(0.06)
Total Potassium	0–10	3.41(0.44)	3.21(0.52)	2.19*(0.58)	2.55(0.38)	2.19*(0.58)
	10–20	3.28(0.39)	3.33(0.35)	2.55*(0.38)	2.62*(0.18)	2.89(0.12)
Total sulphur	0–10	0.12(0.01)	0.11(0.02)	0.11(0.01)	0.17(0.04)	0.11(0.03)
	10–20	0.08(0.01)	0.12*(0.06)	0.11*(0.04)	0.3*(0.36)	0.06(0.01)

Note: Values in the parentheses are standard deviations of samples from four sites in one type of vegetation.

* means that this value is significantly different with that in FA of Alpine tundra at same depth ($p< 0.05$).

Spatial distribution of soil nitrogen

Soil total N of different vegetation types was concentrated mostly at the top of 10 cm depth. Concentrations were similar at FA, LA and TA types, but were significantly higher at MA of 0–10 and 10–20 cm depths, respectively (($p<0.05$) (Table 1, Fig. 1C). The spatial distribution of total N concentration at top surface of 10 cm depth was similar to that at 10–20 cm. However, soil total N concentration increased significantly as FA was changed into MA. More than 41% of soil total N was increased from FA to MA.

Spatial distribution of soil phosphorus

The soil total P concentrations at different depths were significantly ($p<0.05$) lower at LA than those in other vegetation types of Alpine tundra ecosystem. The soil total P concentrations did not vary consistently to total N at the depth of 0–20 cm among the different vegetation types of Alpine tundra ecosystem (Table 1, Fig. 1D). However, total P concentrations for the MA, TA and SA vegetation types was higher at the top layer soil (0–10 cm) than at the depth of 10–20 cm while that for FA and LA types was lower at top layer than at 10–20 cm.

Spatial distribution of soil potassium

Soil total K concentration was significantly ($p<0.05$) higher in FA and LA types than that in TA, MA and SA (Table 1, Fig. 1 E). However, the soil total K had not significant change at different soil depths of each vegetation type. The soil total K concentrations varied contrarily to total P in Alpine tundra ecosystem of Changbai Mountain. Soil total K storage at the depth of 10–20 cm was slightly higher than at the top 10 cm of each vegetation type (Table 2).

Spatial distribution of soil sulphur

Soil S concentration was dramatically higher in MA than that in other vegetation types ($p<0.01$) (Table 1, Fig. 1 F). Soil S concentration had no significant ($p<0.05$) change at different depths of different vegetation types except for MA. The soil S concentration at the depth of 10–20 cm of MA was the highest among all the vegetation types.

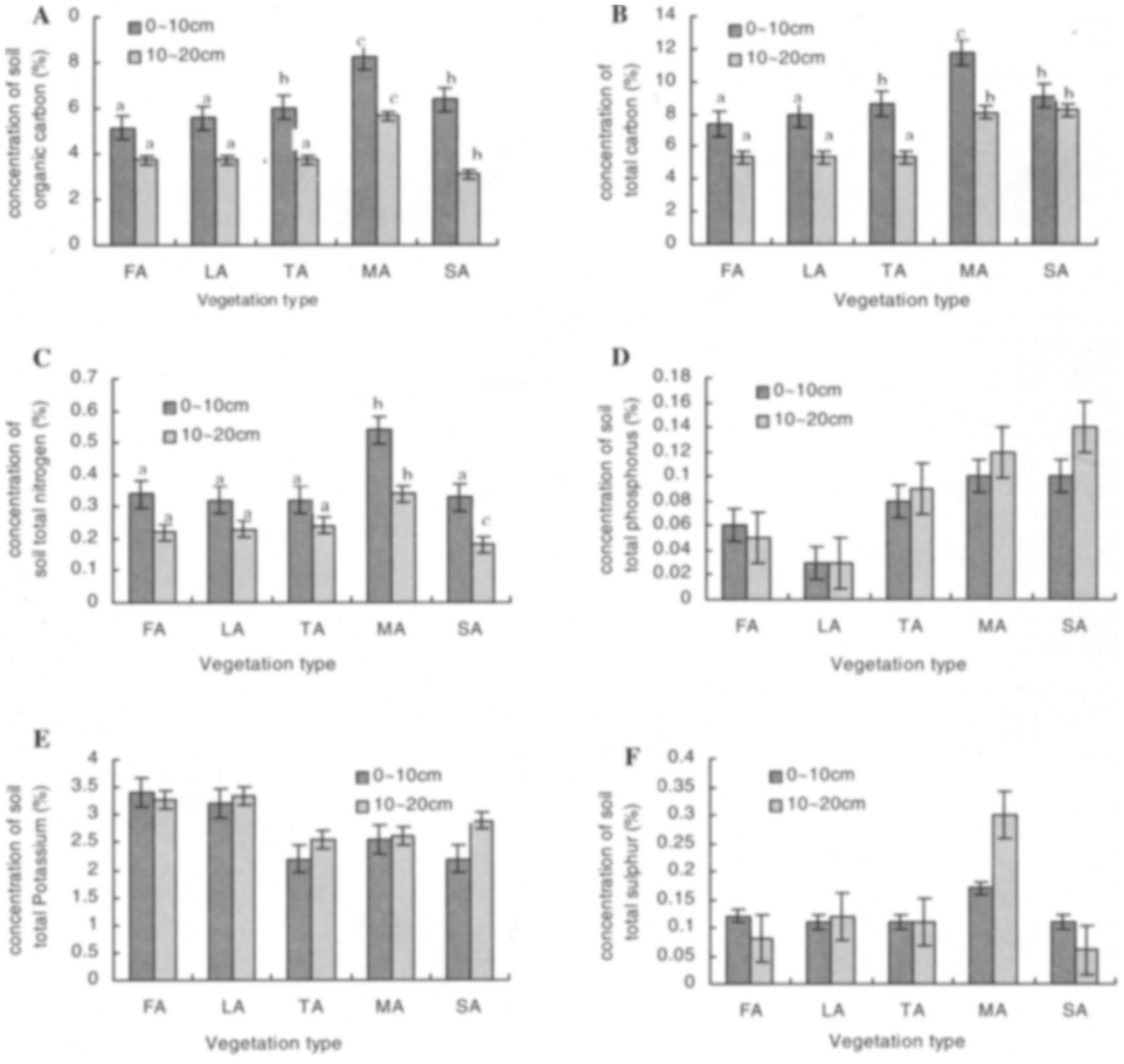

Fig. 1 Concentrations of the organic carbon (A), total carbon (B), total nitrogen (C), total phosphorus (D), total Potassium (E), and total sulphur (F) at different soil depths of different vegetation types

Note: Columns with the same letters (a, b, c) of each soil depth are not significantly different at $p<0.05$

Table 2. Total stocks of soil nutrients at different depths of different vegetation types ($g \cdot cm^{-2}$)

Nutrient	Soil depth /cm	Felsenmeer alpine tundra vegetation	Lithic alpine tundra vegetation	Typical alpine tundra vegetation	Meadow alpine tundra vegetation	Swamp alpine tundra vegetation
	0–10	39.56	45.76	50.57	62.47	47.11
Soil organic carbon	10–20	34.50	30.21	26.63	42.60	17.30
	0–20	73.06	75.97	77.20	105.07	64.41
	0–10	67.24	65.35	72.23	89.30	56.48
Total carbon	10–20	38.09	43.09	48.94	60.90	46.14
	0–20	105.29	108.45	121.17	150.20	102.63
	0–10	3.33	2.62	2.49	4.10	2.05
Total nitrogen	10–20	2.02	1.94	1.63	2.55	1.01
	0–20	5.36	4.57	4.13	6.65	3.05
	0–10	0.59	0.25	0.62	0.76	0.62
Total phosphorus	10–20	0.46	0.24	0.64	0.90	0.78
	0–20	1.05	0.49	1.26	1.66	1.40
	0–10	33.42	26.32	17.08	19.38	13.58
Total potassium	10–20	30.18	26.97	18.11	19.65	16.18
	0–20	63.59	53.29	35.19	39.03	29.76
	0–10	1.18	0.90	0.86	1.29	0.68
Total sulphur	10–20	0.74	0.97	0.78	2.25	0.34
	0–20	1.91	1.87	1.64	3.54	1.02

Changes of the nutrient ratios

For each vegetation type, the ratios of C:N, C:P, C:K and C:S generally decreased with soil depth (Table 3). The ratio of C: N was significantly lower at 0–10 cm and 10–20 cm of all vegetation types except at the top layer of the SA vegetation. The ratio of C: P gradually decreased from FA to SA except for LA. The ratio of C: K gradually increased from FA to SA except for that at the top 0–10 cm of LA and at the 10–20 cm of SA. The ratio of C: S was irregular and its maximum value ocurred at the top 0–10 cm of SA vegetation type.

Table 3. Ratios of C:N, C:P, C:K and C:S at different soil depths of different vegetation types for Alpine tundra ecosystem of Changbai Mountain

Vegetation types	0–10cm				10–20cm			
	C:N	C:P	C:K	C:S	C:N	C:P	C:K	C:S
Felsenmeer alpine tundra vegetation	17.8	100. 7	1.8	50.3	17.1	75	1.14	46.9
Lithic alpine tundra vegetation	16.18	172	1.6	46.9	15.5	124.33	1.12	31.1
Typical alpine tundra vegetation	17.4	69.8	2.5	50.7	16.2	41.4	1.46	33.9
Meadow alpine tundra vegetation	15.2	82.2	3.2	48.4	16.7	47.3	2.17	18.9
Swamp alpine tundra vegetation	19.3	63.8	2.9	58	17.1	22.1	1.07	51.5

Discussion

Change of soil carbon storage

Although plants play an important role in regulating the biogeochemistry of ecosystems by fixing carbon and nutrients and preventing the loss of nutrients under disturbances (Bormann and Sidle 1990; Wedin and Tilman 1990; Chen and Li 2003), the human disturbance and global climate change had great impact on soil carbon and nutrient storage in Alpine tundra ecosystem. In this research we found that soil organic C storage was not consistent with the corresponding net primary productivity per area at each vegetation type. The direct reason is that there were significantly different species, temperature, and water table, etc. However, the indirect reason is possibly that these shrubs and herbs in Typical alpine tundra and Meadow alpine tundra vegetation types, such as *Dryas octopetala* var. *asiatica, Carex atrata, Polygonum ochotense*, may allocate more biomass to roots through waxes and lignins which contain more cellulose to synthesize, and more roots, especially fine roots, can fix more carbon. The litter in MA rapidly decomposed, which also made soil organic C at the surface soil of MA rich. But the fine root biomass was previously included at soil organic C or plant biomass in different researches respectively. In this study the organic carbon of fine root was included in soil organic C according to characteristics of soil respiration in Alpine tundra. The global warming would deeply affect soil organic C, especially the soil organic C of sensitive Alpine tundra ecosystem. Although the global warming could increase the net primary productivity as well as soil organic C decomposition, it did not mean that carbon storage in soil would increase (Chen 1997). The global warming would increase the germination ratio growth of seeds, which made forest extend and tundra contract in the interlaced area of forest and tundra, which was proved by spore researches in North America and Europe during recent 10 000a (Rizzo and Wiken 1992; Ritchie 1987).

Change of soil nutrients

Soil nutrients also changed after human disturbance or

natural disaster because (i) human activities and natural disaster could directly affect soil nutrient decomposition and loss; (ii) after human disturbance, such as trees cutting, soil moisture is easily affected by climate (e.g. the addition of water to dry soil caused large pulsed of CO_2, NO and N_2O emissions (Davidson *et al.* 1993)); (iii) pioneer plants or dominant species have different nutrient requirements, exploit nutrients with varying efficiency and store or convert nutrients at different rates (Chapin 1980; Marschner 1995; Aerts and Chapin 2000). Glazebrook and Robertson (1999) also found that nitrogen of litter decomposing was leached by water flow.

The distribution of soil N has a close relation with root distribution (root clumping and root free zone) (Berger *et al.* 2002). Many studies have shown that nitrogen-fixing species can significantly increase soil N levels (Binkley 1992; Chen and Li 2003), while others found no correlation between the presence of nitrogen-fixing species and total N accumulation in the surface soil (Walker 1993; Cromack *et al.* 1999). In this study we found that soil of the Felsenmeer alpine tundra and Meadow alpine tundra vegetations was abundant of nitrogen and the N accumulation in the surface soil. This possible reason was that nitrogen content of plant and litter was very high while the efficiency of N was relatively low; that there was higher net N mineralization rates from rock weathering during forming soil after volcano eruption; that root zone in fixing nitrogen had special spatial distribution pattern.

Differences in soil P storage may result from change of biological and geochemical processes at different depths after volcano eruption (Frossard *et al.* 1995). In soils mycorrhizal symbionts and other microorganisms closely couple decomposition and uptake processes contributing to soil P retention. Biological controls on P include root growth patterns, amounts and quality of detritus inputs, extracelluar enzyme activity, production of organic chelates and mycorrhizal activity (Binkley 1992; Zou *et al.* 1995). Soil P did not significantly change as vegetation restored. The soil P was lower in Lithic alpine tundra vegetation ecosystem. The soil P was higher at the depth of 10–20 cm in the Meadow alpine tundra vegetation. There was large storage of soil P at MA, SA ecosystems (Table 2). The details of soil P change for each vegetation type appears different and complicated.

Quantitative field estimated of soil K storage at different soil depths of different vegetation types. In this study, soil K was slightly higher in Felsenmeer alpine tundra in comparison with that in other vegetation types. However, soil K was significantly (p<0.05) lower in Swamp alpine tundra vegetation. Therefore, changing Felsenmeer alpine tundra into other vegetation types in this study would increase K release of soil and K absorption of plant. Nutrient-rich plants, branches, twigs and coarse litter fractions are important nutrient sources. The loss of K from litter decomposition was relatively rapid at initial stage and more than 60% of K was released from litter within 6 months and > 75% by 12 months (Liu *et al.* 2000).

Sulphur is considered an essential plant macronutrient. The factors that control the rate of S reduction have not been identified with certainty in the various environments because many factors are involved, such as, oxygen and sulphate concentrations, temperature and organic matter availability (Holmer and Storkholm, 2001). Soil S would come from the mineralization of litter, soil organic matter and rock in the Alpine tundra ecosystem of Changbai Mountain. We also found that S and P content in dominant plants and litter was very high while S and P content in soil was relatively low, which showed that the use efficiency of S and P was significantly high and that S and P were the limited factors of plant growth in the Alpine tundra of Changbai Mountain. Further research should be done to elucidate the relative contribution of soil S and P during vegetation restoration after gigantic volcano eruption in Changbai Mountain.

The ratios of C:N, C:P, C:K, C:S and C:N:P were often used as indicators of soil nutrient condition (Couteaux *et al.* 1995; Glazebrook and Robertson 1999). Also, the initial composition of soil nutrients would affect their decomposition rates (Couteaux *et al.* 1995). Under P deficiency, higher N:P and lignin :P ratios in decomposing leaf litter were associated with lower decomposition rates (Gallardo and Merino 1999). The higher ratios usually mean lower nutrients in the soil. The N and S were lower in SA soil while P, K in LA, MA respectively in Changbai Mountain. The possible reason is that after volcano eruption, soil in this area is mainly oriented with physical weathering while there is hardly any biological and chemical action during forming soil. Furthermore, after vegetation restoration, although the plants grow slowly under low temperature, the anaerobic and reductive soil was against decomposition of litter and microorganism, which made Alpine tundra soil abundant of humus or turf bed.

Although the soil sampling replications were limited in this study, the sampling size satisfied the minimum requirement (5×4) in most of ecological field studies by statistical rule of thumb. However, certain cautions are needed when extending the findings in this study.

Conclusions

As we anticipated, soil organic C appears to reflect changes in vegetation type (plant composition), although the similarities in soil organic C between Felsenmeer alpine tundra and Lithic alpine tundra vegetation or between Meadow alpine tundra and Swamp alpine tundra vegetation would be difficult to anticipate without census information showing the proportionally large number of shrubs and herbs in the community at Lithic alpine tundra or Meadow alpine tundra or Swamp alpine tundra vegetations. The sampling depth and harvesting may account for the fact that soil organic C was lower in Lithic alpine tundra while higher in Meadow alpine tundra vegetation.

Soil N did not vary predictably with the different depths of different vegetation types. We interpreted changeless N concentrations as the result of unlimited factor in the Alpine tundra of Changbai Mountain and higher net N mineralization rates from rock weathering. The P concentrations significantly change among vegetation types. We elucidated that P was the limited factors of plant growth at each vegetation type. The soil of Alpine tundra of Changbai Mountain was abundant of K in Felsenmeer alpine tundra, Lithic alpine tundra vegetation and S in Meadow alpine tundra vegetation, respectively.

The Alpine tundra ecosystems, in general, are vulnerable to impacts of climate change. A greater understanding of the processes at work in the ecosystem is essential to developing better predictive power for this landscape. Further study of the nitrogen and sulphur dynamics of this area is crucial and might include exploration of the specific quality of inputs or outputs by different plant species, as well as decomposition rates and soil properties that affect both decomposition of organic matter and the rates at which litter or humus is rotten.

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